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Determining the displacement of the pelvic floor and pelvic organs during voluntary contractions using magnetic resonance imaging in younger and older women

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Objectives To: (i) visualize the effect of sustained voluntary contractions on the anatomical configuration of the pelvic floor (PF) muscles using magnetic resonance imaging (MRI); (ii) examine the effect of ageing on the range of displacement of the PF contents secondary to contraction and simulating incontinence exercises; and (iii) introduce the concept of contractile change in volume (ΔPF-V) using three-dimensional (3D) reconstruction from axial, sagittal and coronal MRI.

Subjects and methods Two groups of continent women volunteers, familiar with correct PF contraction, were evaluated. The mean (SD) age in group I was 34 (6) years and that of group II 55 (9) years; the mean parities were 0.7 and 2.2, respectively. MRI was conducted with the women supine and data were obtained in the axial, sagittal and coronal planes. In each plane, images were obtained with the PF relaxed and subsequently with the PF contracted over 10–20 s. Image processing was used to enhance the anatomical boundaries of the pelvic organs and to measure the displacement produced by the contraction. Displacements, observed between each image pair, were colour-coded to highlight the geometric differences between a relaxed and contracted PF and to facilitate measuring displacement. Data measured from each group were pooled and the range of motion expressed as the mean (SD), compared using Student's *t*-test.

Results Digitally processed imaging allowed an accurate comparison between the relaxed and contracted PF, and highlighted the differences between them. From these views, the levator ani displaced the vagina asymmetrically in nine of the 11 older subjects, and in six of the 17 younger subjects. The values from the imaging in the sagittal and coronal plane for the two groups were: levator ani displacement, 7.4 (1.1) and 1.4 (0.2) cm ($P < 0.002$), superior bladder wall, 4.2 (0.5) and 1.0 (0.1) cm ($P < 0.002$). There were also significant differences in the range of displacement produced by voluntary PF contraction in the internal structures; external outlines did not reflect these changes. The maximum displacement of the gluteal surface in the coronal plane did not change significantly; in group I it was 3.9 (1.8) to 2.9 (0.7) cm. From the 3D re-construction, ΔPF-V for the younger women was significantly larger, at 23.3 (3.9) mL ($P < 0.01$) than in the older women, at 9.1 (4.4) mL.

Conclusion The range of motion over which voluntary PF contractions displace the bladder and vagina is age-dependent, being higher in younger than in older subjects. It remains to be established whether range of movement is a limitation caused by neuronal factors, decrease in muscle strength/mass, or the substitution of spaces with fat (restricting free movement), or other factors.

Keywords pelvic floor, muscle function, anatomy, MRI, age, women

Introduction

Current MRI studies invariably show the displacement of the pelvic floor (PF) as produced by straining (Valsalva) and consequently represent its passive (acontractile) response [1–4]. While straining is used in the diagnosis of motility and descent, it is of limited value in considering urinary continence, where PF muscles are activated to contract (guarding reflex) by stresses such as coughing [5,6]. Indeed, physiotherapeutic strengthening of the PF, through various exercise regimens and positions, requires the use of repetitive and sustained voluntary contractions instead of straining [7].

The present study was undertaken to visualize PF function during voluntary contractions identical to those during physiotherapy. To identify the three-dimensional (3D) anatomical detail of the PF, separate images were taken in the axial, coronal and sagittal planes, thus cover-

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ing relevant structures between the coccyx and pelvic bones in three orientations [8–11]. The present study was designed to construct a baseline frame of reference for the response of the PF to simulated exercises, using asymptomatic volunteers, and introduces the concept of contractile change in PF volume (ΔPF-V). Because absolute dynamic MRI analysis of the effects of stresses producing urinary incontinence, e.g. coughing, is technologically impractical, we separately captured images of the PF in the relaxed and contracted state. The dynamic changes produced were then approximated using image-processing techniques.

Subjects and methods

Data were obtained from 34 asymptomatic women volunteers; in 16 the mean (SD) age was 35 (6) years and mean (range) parity 0.7 (0–2), and in 18 (peri-menopausal) the respective values were 55 (9) years and 2.2 (1–3), with no previous obstetric and gynaecological history. The research protocol was approved by the ethics committee of the Danish institution.

MR images were acquired with the subject supine, using a 1.5 T system; the field of view was 25 × 25 cm, 7 mm thick with a 7-mm gap and 27 s duration. Subjects were trained by the physiotherapy department to be aware of correct PF contraction and could sustain maximum contraction for 10–20 s. To facilitate image recognition, studies were undertaken when the subject had a full bladder. While fast T2-weighted images would have produced high contrast, because of the number of images required the following protocol was selected. Each image was 256 × 256 pixels; after pilot imaging to identify the subject's alignment, pairs of images in the relaxed and contracted state were obtained. Seven consecutive pairs of images were obtained in the axial plane and five in the sagittal and coronal planes. Between contractions the subject rested for 1–2 min.

The images were analysed using NIH Image V1.54 software and Adobe Photoshop (Mountain View, CA). Individual digital images acquired in each plane were subtracted and the region-of-interest values from the difference image coded. The difference image was subsequently added to the relaxed image and distances measured.

In axial images, displacement values (A) were defined as the range of movement produced by voluntary levator ani contraction, resulting in a posterior to anterior movement. This displacement compresses the rectum towards the vagina and symphysis pubis. Displacement variable LA was defined as the change in the lateral compression of the rectum and vagina. Similarly, in the coronal plane, Ab represents the displacement that is anterior to the bladder and PN represents the displacement that is normal to the posterior of the bladder.

Image processing in the sagittal plane was colour-coded to facilitate visualization of the overlapping regions of PF displacement and regions where contraction resulted in a region being vacated. Processing was designed to show the compressed regions in shades of red and the vacated regions in blue. Thus, the maximum compression produced by the pubococcygeus muscles is shown in deep red while the compression and displacement of the bladder is shown in lighter red. The measurement scheme used for the sagittal plane measurements was defined as: A_S representing the relative changes of the pubococcygeus muscle, B the anterior-dorsal displacement of the bladder and G the change of the gluteus surface.

The axial and coronal planes were used to generate 3D reconstructions showing the change in the path of the pubococcygeus from the pubis to coccyx. From these 3D reconstructions, the change in PF muscle volume was computed and defined as ΔPF-V (axial) or ΔPF-V (coronal). ΔPF-V in a given plane was evaluated by summing the extrapolated images plus the gap between the images.

Mean values were compared statistically for each age group using Student's *t*-test and the values expressed as the mean (SD).

Results

For the axial plane, Fig. 1a represents typical MRI of the relaxed PF at the mid-bladder level, while Fig. 1b shows an MR image obtained at the same anatomical level during a sustained voluntary contraction. The digitally processed image in Fig. 1c shows the difference between the contours of the contracted and relaxed images colour-coded in red and superimposed over the relaxed image. In the plane where Fig. 1c was acquired, the levator ani is seen to compress and displace the rectum and vagina towards the symphysis pubis. The forward displacement (A) and compression by levator ani (LA) were measured in the two age groups; Table 1 shows these variables. From the axial views the levator ani displaced the vagina asymmetrically in nine of the 11 older subjects, compared with six of 17 younger subjects. As is clear in Table 1 the mean values for both A and LA were significantly greater in the younger than in the older group; the maximum value for the displacement of A was 21.9 mm in the younger and 7.8 mm in the older group.

In the coronal plane, as shown by Fig. 2, PF contraction most prominently affected the bladder. This subtracted MR image was acquired in a plane passing though the bladder, designed to illustrate its lateral supporting structures. As shown, voluntary PF contraction symmetrically elevated the bladder. The relative magnitude of bladder displacement from measurements in the two age groups is shown in Table 1. The range of PF movements in the older women was significantly smaller than in the younger group. The

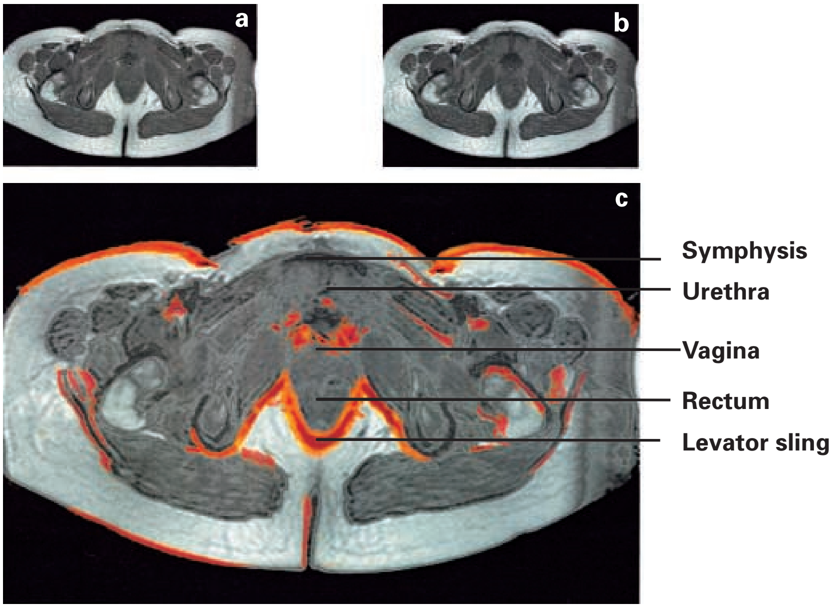

Fig. 1. A composite axial image used to calculate the range of displacement. **a,** Axial MRI view acquired at the level of the vagina with the subject in the relaxed state. **b,** An image at the same level as in A but with the subject voluntarily contracting their pelvic floor. **c,** shows the difference between a and b, and clearly identifies in red the changes produced by voluntary PF contraction.

Table 1 The magnitude and age-dependence of the range of displacement produced by the levator ani, and the changes in displacement of the bladder in the coronal plane and in the sagittal plane

Mean (SD) *displacement, mm*	*Age group*	
	Younger (34 years)	*Older (55 years)*
Levator ani		
A	9.4 (1.2)	2.9 (0.5)†
LA	3.5 (0.5)	1.3 (0.2)†
Bladder		
PN	5.2 (1.2)	1.4 (0.4)†
Ab	5.2 (0.7)	1.5 (0.4)‡
Sagittal plane		
A_S	7.5 (1.1)	1.4 (0.2)‡
B	4.3 (0.5)	1.0 (0.1)‡
G	3.9 (0.5)	2.8 (0.2)

†$P < 0.01$; ‡$P < 0.001$. A; posterior to anterior movement of the levator ani; this displacement compresses the rectum towards the vagina and symphysis pubis; LA, the change in the lateral compression of the rectum and vagina; Ab, displacement of the anterior to the bladder; PN, displacement normal to the posterior of the bladder; A_S, the relative change of the pubococcygeus muscle; B, the anterior-dorsal displacement of the bladder; G, the change of the gluteus surface.

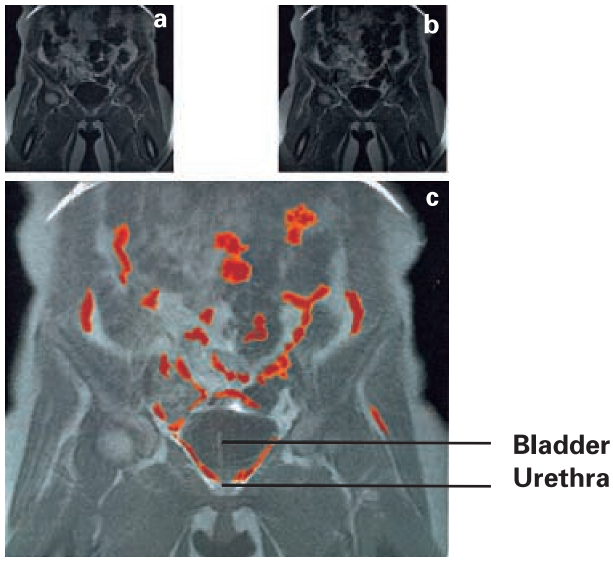

Fig. 2. Superimposed MR images taken in the coronal plane (**a** and **b**) showing the supporting structures of the bladder. The red-coded regions (**c**) indicate the change in position of the levator ani during contractions.

values of PN and Ab were approximately equal, suggesting that displacement is symmetrical at both points of measurement in both age groups. Comparing measurements in the coronal plane with the displacements measured in the posterior/anterior direction (Table 1) and measurements in the axial plane indicates that the range of PF contractions is about double, suggesting a tilting of the bladder towards the symphysis.

In the sagittal plane, the processed MRI produced views of the overlapping regions of PF displacement and regions where contraction resulted in a vacant region. Figure 3 shows a typical processed and subtracted MR image, visualized through the midline, with the compressed regions in shades of red and the vacated regions in blue. Thus, the maximum compression produced by the pubococcygeus muscles is shown in deep red while the com-

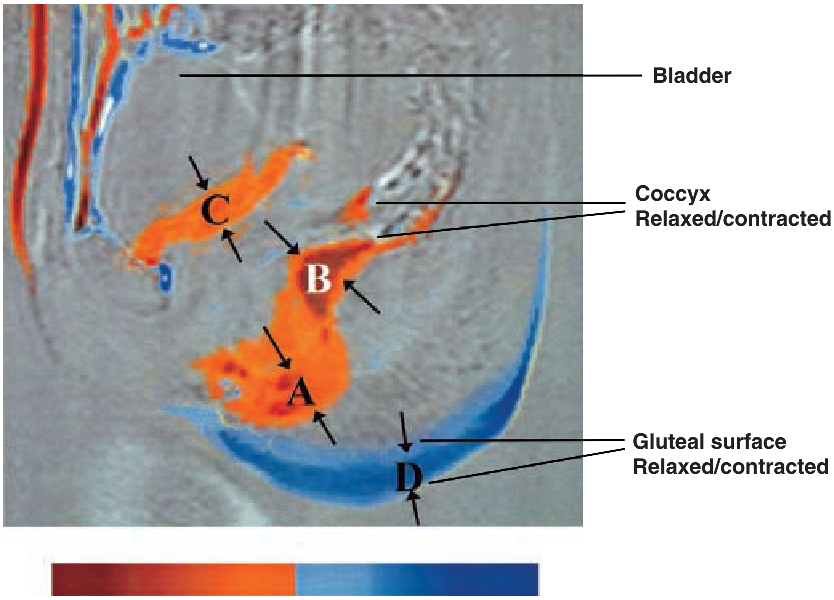

Fig. 3. Image processing at the sagittal plane was colour-coded to produce views of the overlapping regions of PF displacement and regions where contraction resulted in an area being vacated (compressed regions in red and vacated regions in blue). Thus the maximum compression produced by the pubococcygeus muscles are shown in deep red, the compression and displacement of the bladder in lighter red, and where PF contraction vacates the gluteus, in blue.

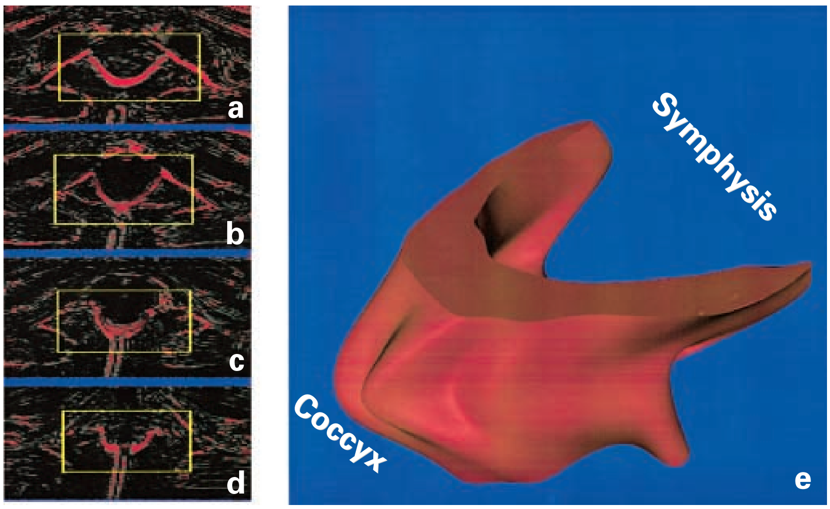

Fig. 4. Axial sequential subtracted MR images (**a**–**d**) showing the configuration of the pubococcygeus muscle. The 3D reconstruction **(e)** shows ΔPF–V (axial) and represents the relative displacement produced by the pubococcygeus muscles. ΔPF–V in this plane was measured within the yellow rectangle.

pression and displacement of the bladder is shown in lighter red. The PF contraction vacates the gluteus (Fig. 3, blue) which also clearly shows the displacement of the coccyx.

Numerical values for the two age groups from sagittal MR images are also shown in Table 1; the range of bladder and levator displacement was significantly dependent on age, but the external displacement produced by the gluteus, while less in older women, was not significantly different from that in the younger subjects.

Figure 4 shows sequential subtracted images of the configuration of the pubococcygeus muscle, originating from the pubis, passing along the urethra, vagina and rectum. The 3D reconstruction (Fig. 4e) shows ΔPF-V, representing the relative displacement of the pubococcygeous muscles approximating the vagina and rectum, as derived from the axial images. As shown in Fig. 4, from the 3D reconstruction, ΔPF-V for the younger group of women was significantly larger, at 23.3 (3.9) mL ($P < 0.01$) than in the older women, at 9.1 (4.4) mL.

Discussion

MRI evidence suggests that the range of motion over which voluntary PF contractions displace the bladder, urethra and vagina is greater in younger women.

Whether the limitation in range among older women is a result of decreased muscle strength/mass, the substitution of spaces with fat restricting free movement, neuronal factors affecting the mechanisms of recruiting maximum contractility, or other causes, remains to be determined. Nonetheless, and in view of the different age of the two groups, the results show that there is a high degree of redundancy in the mobility of the PF before demonstrable urinary incontinence emerges as a clinical problem. Indeed, the extent to which changes in the structure and function of the PF are associated with ageing and the question as to which of these changes are responsible for producing urinary incontinence remains to be further examined in the context of current therapeutic protocols. Furthermore, existing clinical evidence suggesting that stress urinary incontinence improves with PF exercises in some patients but not in others indicates that it is important to identify the conditions of rendering such training effective, and to consider whether the observed variables of contractility and mobility are important. Thus it may be possible to develop a diagnostic test to identify which patients are likely to benefit from PF exercises before embarking on extensive training, which ultimately may prove futile [12,13].

MRI in supine subjects is not directly comparable with recent MRI observations in seated patients [7,14] but the present results agree with those of Bo *et al.* [7] for upright and supine views, i.e. that during contraction, the range of the inward lift is numerically comparable. Straining values had a wider range than voluntary contractions [7,14]. These variances in range may be ascribed to positional differences, the plane in which images were taken, or the absolute intensity of maximum contraction. Overall, the results suggest that MRI yields useful information about the anatomical integrity of the skeletal musculature in terms of both contractility and laxity. We also consider that measuring contractility in upright subjects is more representative than when supine. However, the potential to produce displacement and elicit voluntary PF contractions when supine shows that the neuronal supply is adequate to respond when eliciting voluntary muscle contraction. Intuitively, the best position to evaluate the pelvic floor would be upright, using a fast MRI system capable of acquiring consecutive images at millisecond intervals during stress, e.g. coughing, to visualize the guarding reflex. Until such an MRI system is technologically possible, the combined reconstructions presented here may be used to show the variations in the path of the major muscle groups. Indeed, the calculations made possible from the 3D reconstructions show that the sum total of PF muscle displacement in younger women was significantly larger than in older subjects. Previous measurements of PF mass, reported by Fielding *et al.* [8] were obtained by MRI-based 3D modelling where structures were manually traced. The PF-V approach used here is based on visualizing and quantifying the active volume of the puborectalis muscle and may be more representative of the ability of the PF to respond to the guarding reflex.

The present results were obtained to provide a frame of reference using asymptomatic women in two age groups. The methods used in the study were designed to provide not only anatomical images but also to incorporate functional information. Thus we compared the extent to which the structure and function of the PF is modified with increasing age. Because of the relationship between the incidence of stress urinary incontinence and age, the mechanism of interaction between its anatomical and functional components, e.g. PF laxity, is important [14,15]. The need to functionally document PF laxity focuses attention on the use of the Valsalva manoeuvre during imaging, which we consider a passive and not active response of the PF to the guarding reflex [11,16]. Ultimately, new diagnostic tests to evaluate PF structure and function might require imaging in both the passive and active state. From present observations, we consider it possible to assess: (i) the anatomical integrity of the skeletal musculature in terms of contractility, by eliciting voluntary PF contractions; (ii) the adequacy of the neuronal supply to respond to guarding reflexes; (iii) the biomechanical properties of interconnecting tissues, contributing to its laxity; and (iv) their attachment to the sacral and pelvic structures. Such information would be useful in selecting treatment options to minimize urinary incontinence and to assess the potential benefits of PF in responding to rehabilitation by exercise and training. Overall, having identified several imaging variables, it is essential to identify those which may be useful in selecting treatment and which can predict the outcome of various forms of treatment of incontinence. As the speed of image acquisition increases and critical variable(s) are identified, we anticipate the routine use of simplified MRI to select patients for conservative treatment.

Female urinary incontinence affects 6–20% of the population (depending on the definition), increases in severity with age, and while not life-threatening, compromises quality of life and increases the costs of the healthcare system [17,18]. Options for conservative treatment depend largely on a reliable diagnosis to identify the cause of urine loss [19]. Incontinence caused by urethral incompetence during stress, such as coughing, is most likely to respond to conservative treatment. Conversely, incontinence resulting from detrusor overactivity is more likely to respond to pharmacological treatment, and PF exercises may be redundant [20]. Diagnostic tests of increasing complexity, collectively termed urodynamics, have been developed to identify the cause of incontinence and the magnitude of overactivity. While urodynamic tests are designed to evaluate bladder function in general, systematic approaches in the evaluation of PF function have not been adequately developed [19]. This might be partly because of the number and complexity of interactions between the muscle components constituting the PF, and the accurate identification of their functional significance contributing to incontinence [5,20]. Because of the complexity of the anatomical interactions between PF muscles, various imaging techniques have been used in an effort to assess their anatomical integrity. Among these, MRI has emerged as a viable means of evaluating the PF and has provided the basis for treatment and follow-up [21–23]. Since the initial MRI studies there have been reports of various specialized imaging approaches to provide a better understanding of the 2D anatomy of the PF, with higher spatial resolution and speed of image acquisition [2–4]. However, these 2D views are inherently static and consequently of limited use, particularly in many pathological cases. In 3D MRI sequential 2D images acquired in the axial and sagittal planes are reconstructed [8,9]. Similarly, the mode of action of various devices and electric or magnetic stimulation for therapy rely on the enhancement of the contractility of the PF, presumably to improve its activity during stress. The enhancement of PF contractility would be expected to be reflected in the more effective recruitment of the guarding reflexes [5,6,20,24,25]. The practical importance of PF contractility was validated by Miller *et al.* [26,27] who advocated that patients be educated to undertake voluntary pre-contraction (Knack) as means of minimizing stress incontinence. Physiologically, the practical success of PF pre-contraction in treating incontinence depends on introducing the appropriate temporal priority in responding to stress [16].

In conclusion, we anticipate that the data obtained using this imaging strategy will contribute to the design of MRI approaches for reliably and quantitatively assessing PF function, ultimately aiding the appropriate selection of patients for conservative treatment.

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Abbreviations: **PF**, pelvic floor; **3D**, three-dimensional; **ΔPF-V**, contractile change in PF volume.